

# Technology Selection and Validation: New Millennium Flight Projects

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**Abstract**--NASA's New Millennium Program (NMP) was created to accelerate the insertion of advanced space-related technologies into future science missions by validating these technologies on deep space and Earth-orbiting technology validation missions. The process by which technologies are chosen for validation on NMP flights is complex, because many factors have to be considered. This paper describes the currently approved NMP flight projects and the processes used to select and validate their associated technologies. In addition, the processes being developed to select and validate technologies for future NMP flight projects and the relationships of these processes to NASA technology and science roadmaps will be described.

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1. INTRODUCTION

In 1995 the National Aeronautics and Space Administration (NASA) created the New Millennium Program. The objective of this program is to conduct space flight validation of breakthrough technologies that will significantly benefit future space- and Earth-science missions. The breakthrough technologies selected for validation are focused on 1) enabling new science capabilities to fulfill NASA's Space and Earth Science Enterprise' objectives and 2) reducing the costs of future space and Earth science missions. A secondary objective is to return high priority science data to the extent possible within mission and cost constraints. The Jet Propulsion Laboratory (JPL) serves as the lead center for management of the program.

The goal of space flight validation of these technologies is to mitigate the risks to the first users and to promote the rapid infusion of these technologies into future science missions. Investments made by the NMP will accelerate the

insertion of these high-value, breakthrough technologies into the space and Earth science missions thereby leading to significant leap-ahead scientific capabilities and improvements in mission cost effectiveness. Additional information on the New Millennium Program is available on the Internet [1].

## 2. TECHNOLOGY SELECTION AND VALIDATION PROCESSES FOR CURRENT NMP MISSIONS

### *The Role of Integrated Product Development Teams in Technology Selection and the Development of Flight Hardware and Software*

For the first three and a half years of the NMP, technology selection and flight validation was focused in six technology thrust areas: Autonomy, Telecommunications, Modular and Multifunctional Systems, Microelectronics, In-Situ Instrument and Microelectromechanical Systems, and Instrument Technologies and Architectures. For each thrust area, teams consisting of representatives from government, academia, federally-funded research and development centers, and industry were formed. These teams, referred to as Integrated Product Development Teams (IPDTs), operated as consortia to identify breakthrough technologies, prepare technology roadmaps, and develop flight hardware and software to validate these new enabling technologies in a cooperative and collaborative fashion. Non-NASA members offered specific technologies of interest to the NMP and were selected through a formal source selection process. The organizational membership of these IPDTs is shown in Table 1.

The IPDTs then proposed technologies to be incorporated into the first generation of deep space (DS1, DS2) and Earth-orbiting (EO1) validation missions which are described in the following sections. The proposed technologies were to be funded early enough in the NMP program schedule so that the new technologies did not adversely affect the schedules of the flight projects using the new technologies. The proposed technologies were evaluated for their potential benefit and impact on cost, schedule and overall risk at the end of the concept development phase for each project. The selected technologies were then incorporated into the baseline architectures for these three validation flight projects. It was also recognized that these high risk technologies may

Table 1. Organizational Membership of NMP Integrated Product Development Teams

IPDT	Member Organizations
Microelectronics	USAF Research Lab, Boeing, Georgia Tech, GSFC <sup>a</sup> , Hughes, Honeywell, Irvine Sensors, JPL <sup>b</sup> , APL <sup>c</sup> , GRC <sup>d</sup> , Lockheed-Martin, MIT/LL <sup>e</sup> , Optical Networks Inc., Sandia National Lab, Space Computer Corp., Space Electronics Inc., TRW, Univ. of Calif./San Diego, Univ. of New Mexico, Univ. of So. Calif.
Telecommunications	Boeing, GSFC, JPL, APL, Lockheed-Martin, Raytheon
Modular and Multifunctional Systems	GSFC, Honeybee Robotics, JPL, LaRC <sup>f</sup> , L'Garde, MIT, ARC <sup>g</sup> , NOAA <sup>h</sup> , Primex, SSG Inc., Univ. of Arizona, Univ. of Colorado, USAF Research Lab, Yardney, GRC, Lockheed-Martin Astronautics, NRL <sup>i</sup>
In-Situ Instrument and Micro Electro-mechanical Systems	DARPA, USAF Research Labs, Ball Aerospace, JPL, APL, LANL <sup>j</sup> , National Science Foundation, U. S. Navy Postgraduate School, Sandia National Lab, Southwest Research Institute, Stanford Univ., Univ. of So. Calif./Information Sciences Institute
Autonomy	ARC, Carnegie-Mellon Univ., GSFC, ISX Corp., APL, JPL, Lockheed-Martin, Stanford Univ., TRW, USAF Research Lab.
Instrument Technologies and Architectures	Ball Aerospace, GSFC, ITT Aerospace, JPL, APL, Lockheed-Martin, MSFC <sup>k</sup> , MIT/LL, LaRC, NRL, NOAA, Orbital Sciences Corp., Raytheon, SSG Inc., TRW, Univ. of Wisconsin, NJIT <sup>l</sup>

<sup>a</sup> NASA Goddard Space Flight Center

<sup>b</sup> NASA Jet Propulsion Laboratory

<sup>c</sup> Johns Hopkins University Applied Physics Laboratory

<sup>d</sup> NASA Glen Research Center

<sup>e</sup> Massachusetts Institute of Technology/Lincoln Lab

<sup>f</sup> NASA Langley Research Center

<sup>g</sup> NASA Ames Research Center

<sup>h</sup> National Oceanic and Atmospheric Administration

<sup>i</sup> Naval Research Laboratory

<sup>j</sup> Los Alamos National Laboratory

<sup>k</sup> NASA Marshall Space Flight Center

<sup>l</sup> New Jersey Institute of Technology

encounter unforeseen development problems and that they may eventually have to be deleted from the project baseline architecture to lessen cost and schedule risk.

For those technologies included in the final hardware configuration of a flight project, technology validation agreements were negotiated between the technology providers and the flight project office. These agreements define the success criteria and quantitative performance goals to be achieved in order to successfully validate a technology. In addition the data obtained from these technologies are to be analyzed and disseminated to interested organizations/parties by means of appropriate workshops, NMP technology validation symposia, and peer-reviewed journal papers.

Brief descriptions of the first generation NMP validation missions are given below.

#### *Deep Space 1 (DS1)*

Deep Space 1, the first of the New Millennium missions,

was launched from the Kennedy Space Center on 24 October 1998. This spacecraft, depicted in Figure 1, carries a complement of 12 technologies for validation during the following ten months after launch. These technologies are: 1) ion propulsion system with a suite of diagnostic sensors, 2) solar concentrator arrays, 3) autonomous optical navigation, 4) miniature integrated camera spectrometer (MICAS), 5) plasma experiment for planetary exploration (PEPE), 6) small deep space transponder (SDST), 7) Ka-band solid-state power amplifier (SSPA), 8) beacon monitor operations, 9) autonomy remote agent experiment, 10) silicon-on-insulator low-power electronics experiment, 11) multifunctional structure, and 12) power activation and switching module. These technologies are described in more detail in reference 2.

The ion propulsion system offers significant mass savings for future space missions with high  $\Delta V$  requirements. This propulsion system uses Xenon as the propellant, and at peak operating power consumes 2.3 kW and produces 92 mN of thrust at a specific impulse of 3100 s. Throttling is achieved by balancing thruster and propellant feed parameters at



Figure 1. Deep Space 1 contains 12 technologies for space flight validation. The spacecraft intercepted Asteroid 1996 Braille in July 1999, and the technology validation mission was completed the following September. The Deep Space 1 is now a science mission with the objective of intercepting Comets Wilson-Harrington and Borrelly in 2001.

lower power levels. At the lowest thrust level, 20 mN, the power consumption is 0.5 kW at a specific impulse of 1900 s. The diagnostic sensors will aid in quantifying the interactions of the IPS with the spacecraft, including the advanced-technology science instruments, and in validating models of those interactions.

Due to the high electric power consumption of the ion propulsion system, the DS1 requires a high power solar array. This solar array uses cylindrical silicone Fresnel lenses to concentrate sunlight onto 3600 dual junction GaInP<sub>2</sub>/GaAs/Ge solar cells arranged in strips. The solar array produces 2.5 kW at 1 AU and consists of two wings each of which consist of four (113 cm x 160 cm) panels that are folded for launch. When fully extended, the wings measure 11.8 meters from tip to tip.

The autonomous optical navigation (autonav) system has navigated the spacecraft from shortly after separation from the launch vehicle through the encounter with Asteroid Braille and will be used for navigation to the target comets during the extended mission using data stored in the flight computer or acquired and processed during the mission. The stored data consists of the spacecraft trajectory (generated and optimized on the ground), the ephemerides of the target bodies, about 250 "beacon" asteroids, and all planets (except Pluto) as well as the positions of about 250,000 stars. During the mission, one or two times per week, the spacecraft is turned to point the MICAS sequentially at 4 to 20 "beacons". Visible images from the MICAS are processed and combined with other information to determine the location of the spacecraft. Autonomous navigation permits a significant reduction in the cost of NASA science missions by reducing the need for tracking by the Deep Space Network (DSN).

The MICAS is a advanced 12-kg instrument that includes two visible imaging channels, an ultraviolet imaging spectrometer, and an infrared imaging spectrometer plus

electronic and thermal controls. All sensors share a common 10-cm- diameter telescope. This instrument contains no moving parts since the structure is fabricated from thermally stable silicon carbide.

The PEPE combines multiple plasma physics instruments in one compact 5.6-kg package to determine 3-dimensional plasma distribution over its field of view; it also assists in determining the effects of the IPS on spacecraft surfaces and instruments and on the space environment, including interactions with the solar wind.

Three telecommunications technologies were included on the DS1 for validation. The small deep-space transponder combined the receiver, command detector, telemetry modulator, excitor, beacon tone generator (for beacon monitor operations, another technology validated on the mission), and control functions into one 3-kg package. The SDST allows X-band uplink and both X-band and K<sub>a</sub>-band downlink. The Ka-band solid-state power amplifier serves as a secondary downlink to Earth and is the highest power device of this type ever used for deep space communications. The SDST generates tones used for beacon monitor operations, a operational concept conceived to reduce the heavy demand expected on the DSN if many missions are flown simultaneously as envisioned by NASA. In this operations concept, an on-board data summarization system determines the overall health of the spacecraft and then transmits one of four tones to indicate to the operations team (on Earth) the urgency of the need for DSN coverage for the spacecraft. Without data modulation, these tones are detected easily with small, low-cost systems, reserving the large, more expensive DSN stations for command uplink and data reception when the beacon indicates that such attention is required. The four tones correspond to a) all is well, and no assistance is required, b) a unusual but not threatening event has been encountered, c) intervention is needed to prevent loss of data or assist in resolving a threat to the mission, and d) immediate assistance is required because the spacecraft has encountered a mission-threatening emergency it was unable to solve.

The remote agent experiment, a on-board artificial intelligence system for planning and executing spacecraft activities, is the third autonomy technology to be validated on the DS1 mission (the other two are autonomous optical navigation and beacon monitor operations). This technology uses an agent of the ground team and includes an on-board mission manager that carries the mission plan expressed as high-level goals. A planning and scheduling engine uses the goals, comprehensive knowledge of the state of the spacecraft, and constraints on spacecraft operations to generate a set of time-based activities that are delivered to the executive. The executive then creates a sequence of commands that are issued directly to the appropriate destinations on the spacecraft. The executive monitors the responses to the commands and reissues or modifies them as required. A mode identification and reconfiguration engine aids in assessing the spacecraft state and in recovering from

faults without requiring help from the ground except in extraordinary cases. This remote agent was tested in a restricted case on DS1, in preparation for more ambitious experiments on future flights.

The low-power electronics experiment was developed to characterize the effects of the space environment on sub  $0.25\mu\text{m}$  fully depleted silicon-on-insulator CMOS test devices that operate at supply voltages of less than two volts. The multifunctional structure is an experiment to evaluate the concept of folding spacecraft electronics into the walls of the spacecraft, thereby saving weight and space by eliminating chassis, cables and connectors. The power activation and switching module enables significant miniaturization of spacecraft electrical load and switching functions by eliminating bulky relays and fuses that have been used in the past. A 3-D computer stack, which included a number of advanced component and packaging technologies, was also scheduled for validation, but, due to unforeseen technical problems and schedule delays, was replaced with a flight computer similar to that used on the Mars Pathfinder mission.

Operational results from the DS1 technology validation mission are summarized in reference 3.

#### *Deep Space 2 (DS2)*

Deep Space 2, the second of the New Millennium missions, was launched from the Kennedy Space Center on 3 January 1999 and is scheduled to arrive at Mars the following December. The objective of this mission is to demonstrate: 1) key technologies that enable future network science missions (such as multiple landers, penetrators or spacecraft), 2) a passive reentry system, 3) highly integrated microelectronics capable of surviving high-g impact and operating at extremely low temperatures, and 4) in-situ subsurface data acquisition. The primary science objectives are to determine if water ice is present below the Martian surface and to characterize the thermal properties of the Martian subsurface soil.

This mission consists of two 3-kg indentical microprobes, one of which is shown in Figure 2, attached to a mother ship that also carries the Mars 98 Polar Lander spacecraft. Approximately 10 minutes prior to landing, the probes separate from the mother spacecraft, descend through the atmosphere without the benefit of either parachutes or airbags, and survive a high-g impact near the northern boundary of the southern Martian polar region. The probes are protected during entry in the Mars atmosphere by a advanced non-ablative heat shield. At impact on the Martian surface, the heat shield will shatter, and the probes will separate into two parts; one part (the aft-body) will remain on the surface and the other part (the fore-body) will penetrate approximately 1 meter into the Martian soil. The fore- and aft-bodies are expected to experience shock loads of about 30000 g's and 60000 g's respectively. Instruments

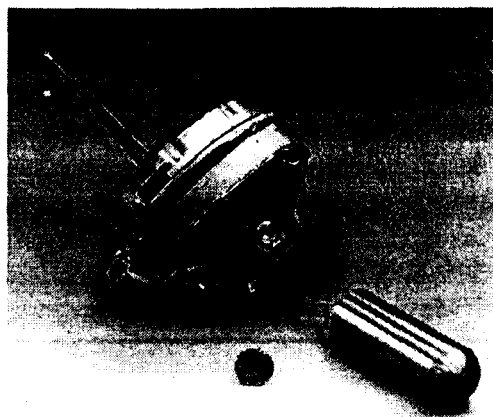


Figure 2. Deep Space 2 Mars Microprobe. At impact, the aft-body (left) will remain on the Martian surface, and the fore-body (right) will penetrate into the subsurface soil to detect the presence of water. A multi-layer flex cable connects the two sections electrically.

in the fore-body will attempt to determine the presence of water ice and to measure the vertical temperature gradient in the soil. Data from these instruments is transmitted via a advanced multi-layer flex cable to a radio beacon in the aft-body. The beacon relays the data to the Mars Global Surveyor spacecraft, which, in turn, relays the data back to Earth. Microelectronics play a key role in the Deep Space 2, and the microelectronics technologies to be validated on this mission are 1) an advanced microcontroller, 2) a power microelectronics unit, and 3) the evolved water experiment with its associated electronics. All of these technologies are located in the fore-body mentioned previously. The evolved water experiment uses a novel drill mechanism to acquire sub-surface samples that are then heated in a small crucible to release water if present. A tunable diode laser is used to detect the presence of water vapor. The advanced microcontroller controls operation of and stores data produced by the evolved water experiment and the temperature sensors and sends the data to the radio beacon for transmission to the Mars Global Surveyor, which was launched in 1996. The power microelectronics unit provides power management (power is provided by advanced lithium/thionyl chloride primary batteries located in the aft-body), distribution and conversion for the evolved water experiment, temperature sensors and the advanced microcontroller. Some of the unique electronics packaging aspects of the electronics in both the fore-body and the aft-body are described in reference 4.

#### *Earth Orbiting 1 (EO1)*

Earth Orbiting 1, the third of the New Millennium missions and illustrated in Figure 3, is scheduled for launch from Vandenberg Air Force Base in February 2000 with three advanced land imaging instruments and a complement of eight advanced spacecraft technologies. The three advanced imaging instruments, the Advanced Land Imager (ALI), the Atmospheric Corrector, and the Hyperion



Figure 3. Earth Orbiting 1. This spacecraft will validate technologies contributing to the reduction in cost of future Landsat missions.

(hyperspectral imager) will lead to a new generation of light weight, higher performance and lower cost Landsat type instruments for NASA's Earth Science Enterprise. The ALI employs novel wide-angle optics and a highly integrated multispectral and panchromatic spectrometer. EO1 is a technology validation mission designed to demonstrate comparable or improved Landsat spatial and spectral resolution with substantial mass, volume and cost savings. Earth imagery is degraded by atmospheric absorption and scattering, and the EO1 will provide the first space-based test of an Atmospheric Corrector for increasing the accuracy of surface reflectance estimates. The Hyperion is capable of resolving 220 spectral bands (from 0.4 to 2.5  $\mu\text{m}$ ) with a 30-meter resolution. This instrument can image a 7.5-km x 100-km land area per image and provide detailed spectral mapping across all 220 channels with high radiometric accuracy. The advanced spacecraft technologies, which include a X-band phased array antenna, a carbon-carbon composite radiator, a lightweight flexible solar array, a pulsed plasma thruster and enhanced formation flying capability will enable smaller, lower weight and reduced spacecraft power buses. A wide band advanced recorder processor (WARP) receives data from the three instruments at up to 840 Mbits/sec, then formats and stores the data in its 40 Gbit solid-state recorder. The WARP includes a 10 MIP processor capable of processing science data as well as a lossless 2:1 data compression chip. The data will be sent to the ground via the X-band phased array antenna at 105 Mbits/sec and subsequently sent to GSFC for technology validation and science research. A fiber-optic data bus (FODB) was developed as a high-speed (up to 1 Gbit/sec) data interface for future spacecraft. The FODB is based on a ring topology of 2 to 128 nodes which provides a thousand-fold higher data rate than the flight proven Mil-Std 1773 fiber optic data bus as well as flexibility to meet different payload requirements. The interface between nodes is entirely fiber optic, which reduces weight and provides for a system free of EMI/EMC problems. The FODB was developed to comply with IEEE P1393 Spaceborne Fiber Optic Data Bus Standard which specifies a highly reliable fault tolerant fiber optic network that is

compatible with the harsh thermal, mechanical, and radiation environments of aerospace applications requiring small size and power dissipation. The FODB implements an asynchronous transfer mode (ATM-based protocol) with minimum overhead which simplified node interface design. The FODB was scheduled for validation on EO1 as the primary science data path between the three instruments and the WARP, but was deleted from the final spacecraft configuration due to unforeseen technical problems and schedule delays. Parallel EIA RS-422 interfaces (originally redundant to the FODB) now provide the data path between each of the three instruments and the WARP.

Earth Orbiting 1 will fly in formation with the Landsat 7 and provide 100-200 paired scene comparisons with the ETM+ instrument on the Landsat 7.

### 3. TECHNOLOGY SELECTION AND VALIDATION PROCESSES FOR FUTURE NMP MISSIONS

#### *Background*

Subsequent to the establishment of the New Millennium Program in 1995, NASA published a strategic plan [5] that defines the Agency vision, mission, and fundamental questions of science and research that are the foundation of Agency goals to be accomplished over the 25 years spanning 1998 to 2023. This plan also describes the four Strategic Enterprises to manage programs and activities that will implement the mission. The Strategic Enterprises are Space Science, Earth Science, Human Exploration and Development of Space, and Aeronautics and Space Transportation Technology. These enterprises have published their respective strategic plans that include comprehensive science and focused technology roadmaps for proposed future missions.

NASA also created the Cross-Enterprise Technology Development Program (CETDP) to focus on technology development in support of multiple Enterprise customers. Typically, CETDP acts to develop critical space technologies that enable innovative and less costly missions and enable new mission opportunities through revolutionary, long-term, high-risk, high-payoff technology advances. Many of these technologies are at the very early stages of development and may be viewed as technologies of opportunity ("technology push") rather than as required technologies identified in the Enterprise focused technology roadmaps.

The NASA Strategic Enterprises and the CETDP are now responsible for developing technology roadmaps which were previously a key function of the IPDTs. In addition the technology acquisition process for future NMP flight projects was simplified by using the familiar NASA Research Announcement (NRA). As a result, the IPDTs will be disbanded, and NMP has developed a new process for selecting technologies for space flight validation and formulating technology validation missions that support the

goals of the Space Science and Earth Science Enterprises. The processes developed by the NMP for technology selection for future validation missions is described in this section. For illustrative purposes, the entire process for technology selection, flight project formulation and flight project initiation will be briefly described in the context of project formulation activities for the Space Technology 5 (ST5, formerly referred to as Deep Space 5) and EO3 projects.

### *Technology Selection Process*

**Flight Validation Domain**—The number of systems, subsystems, or components that might be flight validated is very large. The reasons for flight validation range from “cannot be tested on the ground” to “lack of flight heritage” due to an advance in the technology or to procedural change in hardware assembly or mission operations. Thus, a rational and equitable selection process is required to allow an orderly and open selection of technologies for flight validation on NMP missions.

As depicted in Figure 4, the technology selection process begins with aligning emerging technologies being

developed by NASA, other government agencies, universities and industry with the science capability needs of the Space and Earth Science Enterprises. Emphasis is placed on identification of emerging high-risk, high-payoff breakthrough technologies. Using flight validation justification factors, described later, the candidate breakthrough technologies for flight validation are identified, and NMP will flight validate only a small portion of those candidate technologies.

**Technology Selection Process**—An overview of the NMP process for planning and implementing technology validation flights is shown as a high-level block diagram in Figure 5. A more detailed diagram for identification of candidate technologies for flight validation and capturing flight validation concepts (the first block in Figure 5) is shown in Figure 6. This “pre-project” planning process consists of first identifying the technologies for flight validation and capturing potential flight concepts. This portion of the process is the subject of this section. After the identification stage, flight projects, as opposed to flight concepts, are formulated, then chosen, and finally the projects are implemented as shown in Figure 7.

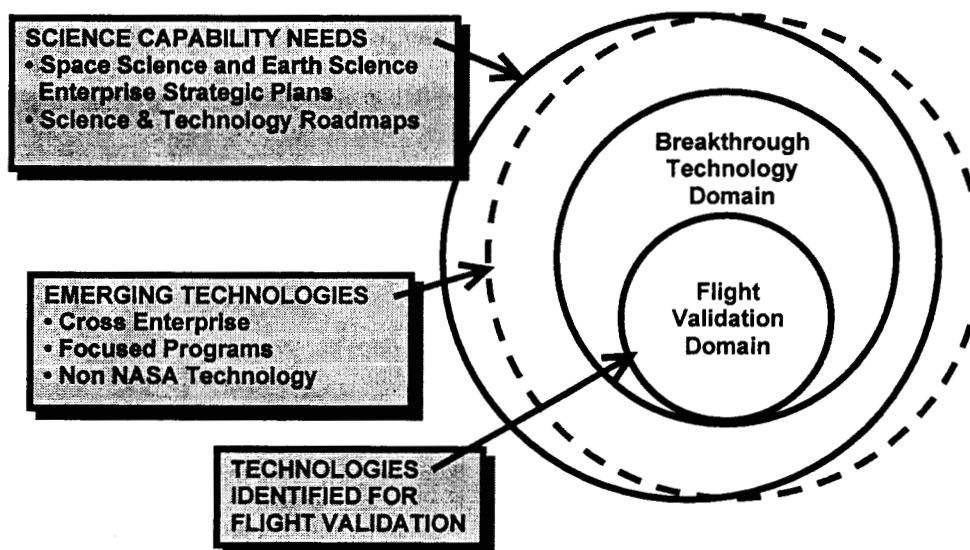


Figure 4. The relationship between the technology development domain and the identification of candidate technologies for space flight validation on NASA NMP missions.

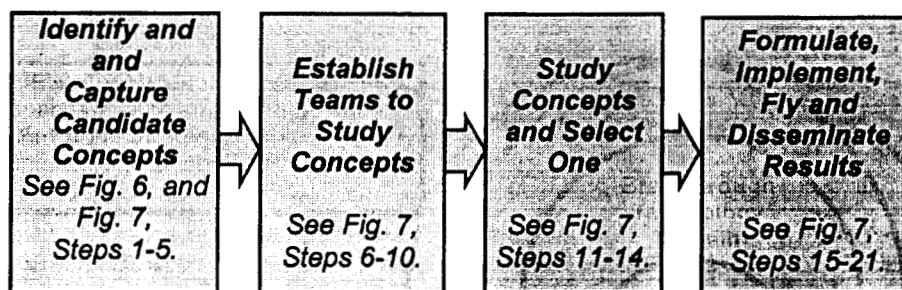


Figure 5. NMP planning and implementation processes for technology validation flights.



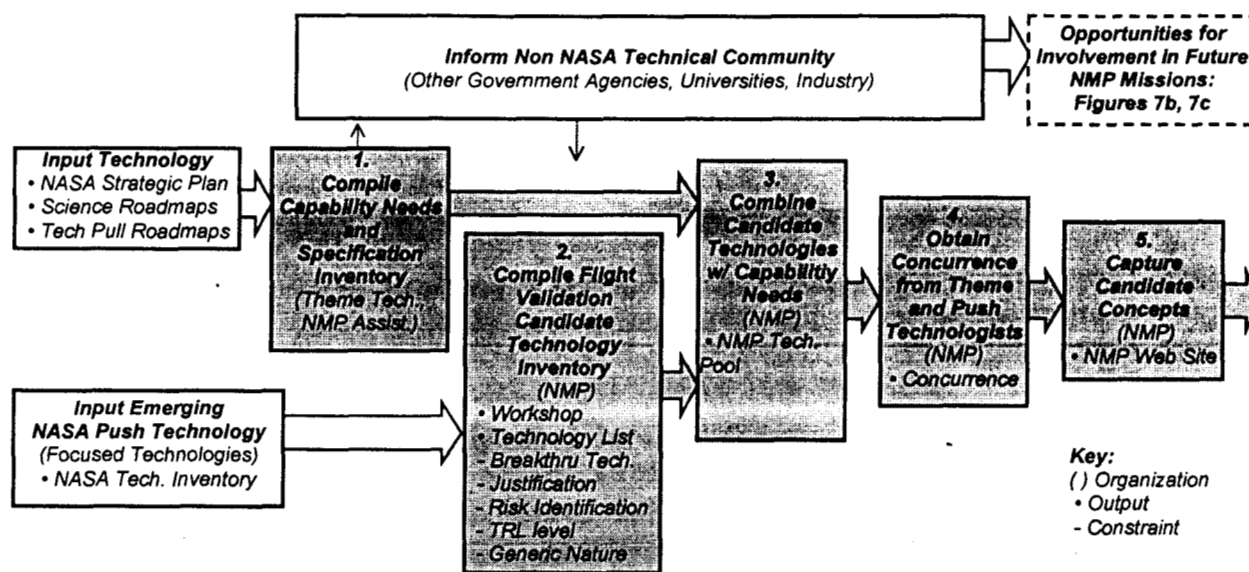


Figure 6. NMP pre-project planning process for technology identification and capture of flight validation mission concepts.

The process for identifying flight validation technologies and assimilating them into candidate flight validation missions is shown in Figure 6. The process begins in step 1 where the NASA Enterprise Theme technologists with assistance from the NMP staff review the technology and capability needs identified in the Strategic Enterprise (science and technology pull) roadmaps and compile a capability needs and specification inventory. The results in this inventory are made available to the non-NASA technical community for informal comment and feedback on relevant technology developments taking place outside NASA. Opportunities for the non-NASA technology community to contribute to NMP flight projects are shown in Figure 7. In parallel, in step 2, a list of candidate technologies for flight validation is compiled, in a workshop setting, from information in the NASA Technology Inventory. The formal mechanism for establishing the NMP technology inventory is currently under discussion.

The compilation process in step 2 is constrained and guided by several factors: (a) breakthrough technology considerations, (b) generic nature of the technology, (c) flight validation justification factors, (d) risk identification, and (e) TRL (Technology Readiness Level). Breakthrough factors include considerations such as technology performance and cost. The generic nature is determined by the support shown by the Enterprise Theme technologists. The risk identification factors are customer focused and are meant to determine the degree to which the technology will be utilized. The maturity of the technology is indicated by the Technology Readiness Level described in Table 2. The flight validation justification factors are discussed below.

The justification factors used in step 2 are a key requirement

in the technology selection process. These factors are summarized below. Only one of these factors is necessary to justify flight validation.

**Environmental Factor** (Ground Test Impossible): These technologies are the ones that cannot be adequately tested, simulated or modeled on the ground. Therefore, they have high risk for inclusion in future science projects and thus are prime candidates for flight validation. The sub-factors concern steady-state effects, transient effects, external interactions or reliability issues. Persistent environments are either time invariant such as zero gravity or periodic such as experienced by a spinning spacecraft. Transient environments are those effects that cause a step-function stress on a system, such as transient temperature effects, that causes mechanical distortions in highly aligned structures. The transition between persistent and transient environments depends on the time scale of the observer.

External interactions occur when the spacecraft utilizes the space environment for some purpose such as solar wind propulsion or atmospheric aero-assist. These interactions are very difficult to duplicate either via ground tests or computer simulation.

Part of the mission for the NMP test flights is to characterize the reliability of components and systems in a space environment. However, the duration of the NMP test flights will generally be short in duration compared to the desired operational life. Space tests for reliability evaluation must describe how space tests will provide more data than ground tests and should include diagnostic sensors to measure small degradations in performance during NMP test flights so that NMP results can be used to predict the

Table 2. Technology Readiness Levels

<b>TRL 9: Actual system "mission proven" through successful mission operations (ground or space)</b>	Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.
<b>TRL 8: Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space)</b>	End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. V&V completed.
<b>TRL 7: System prototype demonstration in operational environment (ground or space)</b>	System prototype demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.
<b>TRL 6: System, subsystem model or prototype demonstration in a relevant end-to-end environment</b>	Prototype implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.
<b>TRL 5: System, subsystem, component validation in relevant environment</b>	Thorough testing of prototype in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototype implementations conform to target environment and interfaces.
<b>TRL 4: Component, subsystem validation in laboratory environment</b>	Stand alone prototype implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.
<b>TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept</b>	Proof of concept validation. Active R&D is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard/brassboard implementations that are exercised with representative data.
<b>TRL 2: Technology concept and/or application formulated</b>	Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.
<b>TRL 1: Basic principles observed and reported</b>	Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.

performance of long-life projects.

**Paradigm Shifts:** Technology is often deemed unacceptable for space flight if there is a significant change in the design approach or manufacturing procedure. Because of these factors, project managers are unwilling to include such "new" technologies in their projects until the technology has demonstrated to have a tolerable risk/reliability when flown. Paradigm shifts are changes in the design, fabrication, assembly, and operations that differ significantly from current practice. For example, the ground operations for a continuously operated ion engine are significantly different from burst and glide propulsion.

**Interdependency/Complexity Factor (Combined Effects):** Complex technologies consist of assemblies whose components are usually adequately ground tested but the complete assembly or system cannot be adequately ground tested. Testing becomes complex when components interact or cross talk and this can result in a large number of tests.

Testing is further compounded when complex systems have autonomous control. This factor involves cross-talk issues where one subsystem affects another. Ground tests generally identify the sensitivity of such interactions taken one at a time but may not characterize effects applied more than one at a time. The advantage of a ground test is that effects can be applied over a larger dynamic range than encountered in space. Thus, there must be a strong justification to test in space.

The candidate technology list that is compiled in step 2 is then combined (in step 3) with the capability needs/specification inventory developed in step 1, and concurrence with the Enterprise Theme technologists and the CETDP technology area managers is obtained in step 4. In step 5, the results are assimilated into a list of candidate flight validation concepts. These flight validation concepts will also be published on the NMP web site. The inventory in step 5, will contain the following elements: (a) technology description, (b) performance characteristics,



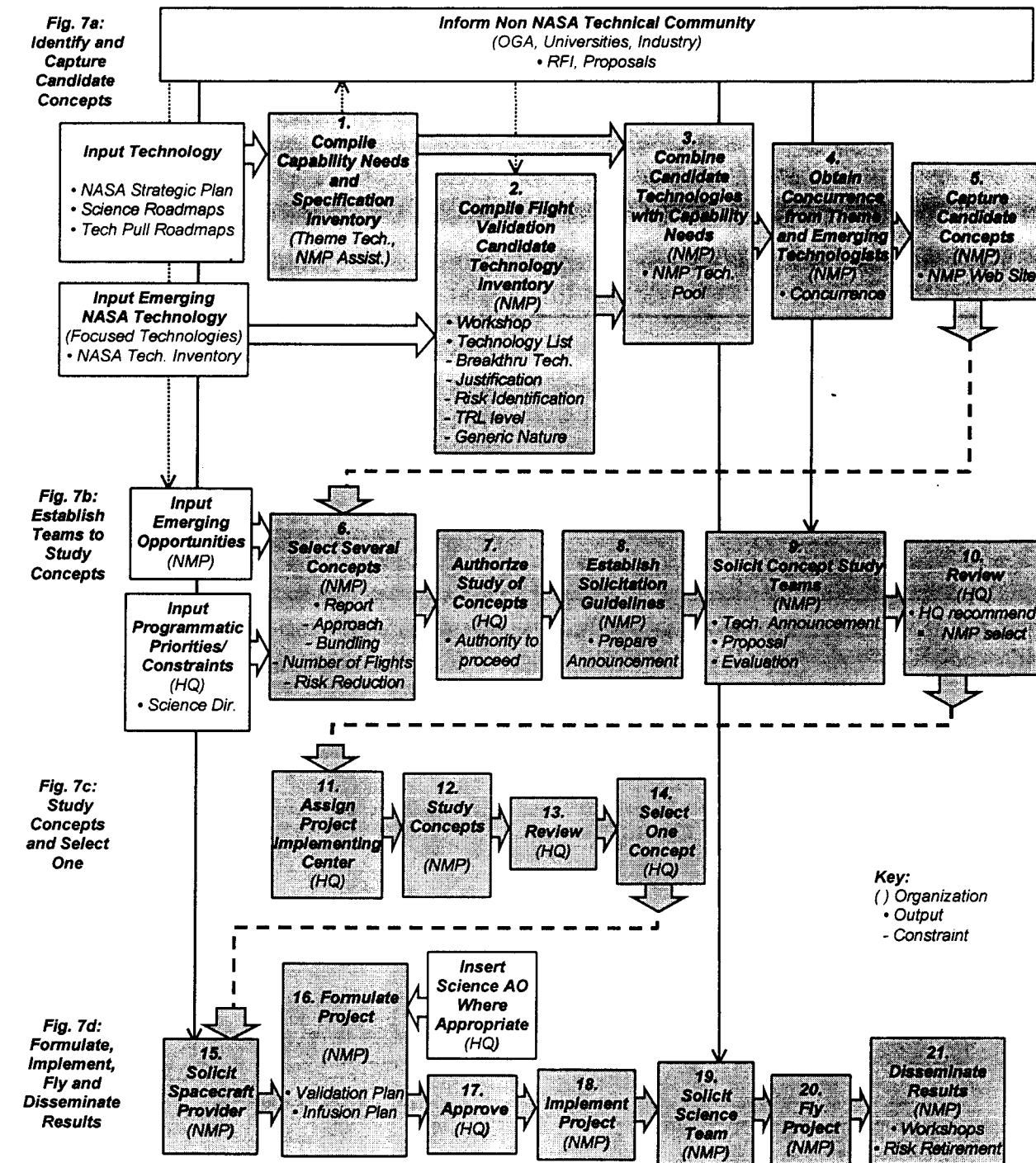


Figure 7. Detailed View of the NMP Technology Selection, Project Formulation, and Project Selection Processes for Technology Validation Missions.

(c) flight justification, (d) generic nature, (e) technology readiness level, (f) description of the part of the technology that requires flight validation, and (g) risk including ROM (rough order of magnitude) cost.

#### Flight Project Formulation and Implementation

The evolution of the flight validation concepts (developed in step 5) into the formulation and implementation stages of a

NMP flight project is shown in Figure 7. Sections of this process were exercised during the recent acquisition activities for ST5 and EO3 and will be discussed later in this section.

The candidate flight validation mission concepts developed in step 5 are further refined using feedback received from the non-NASA technology community and programmatic priorities and constraints established by NASA Headquarters. Several of these concepts are then selected in step 6 and a report on the selected concepts is prepared by the NMP staff. This report contains details on the approach for each proposed mission, the technologies bundled in each concept and the risk reduction approach for each concept. This report is submitted to NASA Headquarters for review, and two or more of these concepts are then selected for continuation into the project formulation phase.

The NMP staff then prepares solicitation guidelines (step 8) for the formation of concept study teams. These guidelines consist of a technology announcement which will be posted to the NMP web page, the Commerce Business Daily (CBD), and the NASA Research Opportunities web page [6] and other documents for NASA internal use in evaluation of proposals in step 9.

Membership in concept study teams is open to US industry and academia, NASA centers, other US government agencies, non-profit organizations, and Federally-Funded Research and Development Centers (FFRDCs). These organizations are encouraged to propose technologies that meet the needs of the mission concepts described in the technology announcement. Members of these organizations may serve in either a proposal submission or a proposal evaluation role but not in both during any given solicitation. The proposed technologies should be at technology readiness level 3 or 4 (see Table 2) and have a realistic plan to reach level 7 in time to support launch of the mission.

A draft technology announcement is first posted to the NMP web page and other information sources mentioned above. The final draft of the technology announcement is posted approximately one week later. Proposals are due approximately 3 weeks after the final draft is posted. A mail-in process is used in step 9 for the evaluation of proposals. The proposals are purposefully kept short to approximately 8 single-sided pages total to facilitate rapid proposal evaluation. All proposals are peer reviewed, and reviewers are chosen from the above mentioned organizations. Reviewers from industry do not review proposals from other companies, and reviewers do not review proposals from his/her organization. The proposal review process is completed in approximately three weeks, and a proposal summary report is prepared for review by NASA Headquarters. Recommendations for membership on the concept study teams are made by NASA Headquarters, and formal membership selection is made by the NMP (step 10). At this time, NASA Headquarters also assigns leadership responsibility to a NASA center for each

of the concept study teams (step 11).

In step 12, each of the concept study teams works to refine their respective concepts and develop a detailed concept proposal. This concept study phase lasts for approximately 3 months. During this study phase it may be found that all of the technology validation goals cannot be achieved due to either funding or technology readiness constraints. Thus it is possible that some technologies selected in step 10 will not be included in the final concept proposal. The suppliers of those technologies that are included in the final concept proposal will be funded to supply the flight articles if the concept is selected in step 14.

In step 13, the concept proposals prepared by the concept study teams in step 12 are reviewed by NASA Headquarters, and one concept is selected for detailed project formulation (step 14).

Once a flight validation concept is selected, a solicitation for a spacecraft bus provider will be conducted (step 15) if this is required for the mission. A detailed project plan is prepared in step 16. This plan includes detailed schedules, cost estimates, a technology validation plan including technology validation agreements with the technology suppliers selected in step 10, a technology infusion plan, and a risk management plan. At this point, if there is sufficient justification, science instruments may be included in the mission. The science instruments will be acquired through the standard NASA AO (Announcement of Opportunity) process. These plans are submitted to NASA Headquarters for approval, and implementation of detailed design, fabrication, and software development activities take place in step 18. If science measurements are included in the mission, the science team is formed (by means of the NASA AO process) in step 19. Launch and mission operations occur in step 20, and, after the mission is completed, the technology validation results are disseminated by the means mentioned previously.

The process outlined in Figures 5 - 7 is still evolving. This process was not fully in place at the time of the ST5 and EO3 acquisition activities described below, and there are some aspects unique to the NASA Office of Earth Sciences that are not shown in these figures but will be discussed in the following discussion of the EO3 project. The lessons learned from these activities have been factored into processes described above.

*Space Technology 5 (ST5)*—Planning activities for ST5 essentially began just before step 6 in Figure 7. A small team consisting of NMP staff and scientists associated with the Sun Earth Connection (SEC) and Structure and Evolution of the Universe (SEU) science themes of the Office of Space Science was established in late 1998 to formulate concepts for candidate technology validation missions to be launched in FY 2003. In January 1999, NASA Headquarters selected the solar sail, constellation of small satellites, and disturbance reduction concepts,

authorized the formation of study teams for each of these concepts and established a budget cap of approximately 29 M\$ for project implementation (steps 15 - 21, Figure 7d).

Solar sail technology enables previously nonviable space mission concepts and provides a lower cost alternative for future science missions with high  $\Delta V$  requirements. Such missions use the sun's inexhaustible supply of photons to enable missions with non-Keplerian orbits and orbits that offer unique vantage points. Flight validation is required for: (a) sail deployment, (b) functionality and performance of the sail as a propulsive device, (c) sail vehicle system functionality and performance including the effects of the sail on spacecraft instruments and systems, (d) sail functionality for extended in-space station keeping, (e) sail jettison, and (f) delivering data from a sub-L1 orbit location on the sun-earth line. Solar sail propulsion enables a number of future SEC missions including Solar Wind Sentinels, Solar Polar Imager, and Heliopause Explorer. Team leadership responsibility for this concept was assigned to the Jet Propulsion Laboratory.

Constellations of small intelligent satellites that measure the particles and fields at the boundary of the Earth's magnetosphere have been identified as a major technology focus for 21<sup>st</sup> century SEC missions. Small satellites are defined as those having a mass of about 10 kg and average available power of 10 watts. Technology validation issues are the ability to build, deploy, coordinate, control, and reposition the small satellites and to minimize costs to manufacture, launch, and operate them. Magnetic and electrostatic cleanliness are also important. The ST5 concept for a constellation of small satellites will demonstrate the performance of multiple small satellites each of which has a mass of 10 - 20 kg and available power of 10 - 20 watts. Launch opportunities may result in orbits that range from Geosynchronous Transfer Orbit (GTO) to other highly elliptical orbits. The first SEC mission to benefit from this technology validation concept is the Magnetospheric Constellation currently planned for launch in 2007. Team leadership responsibility for this concept was assigned to the NASA Goddard Space Flight Center.

The disturbance reduction concept would validate key technologies required for gravitational-wave detection missions planned for 21<sup>st</sup> century SEU missions. These gravitational waves can be detected by measuring changes in the distance between proof masses induced by passing gravitational waves. The focus for this concept is directed at reducing the perceived technology risk of producing and operating a very high performance inertial sensor. The inertial sensor consists of a proof mass and a means of measuring the position of the proof mass with respect to its housing. The performance of the inertial sensor is determined by how closely the proof mass follows a trajectory determined by gravitational forces only (a geodesic). To validate this performance of the inertial sensor, it is necessary to compare the trajectory of its proof mass to a reference geodesic. In this concept validation

would be accomplished by including a second inertial sensor within the same spacecraft. With the spacecraft controlled to stay centered about one proof mass, the distance between the proof masses can be measured with picometer accuracy with a laser interferometer to see if both proof masses are following the same trajectory. The disturbance reduction concept is a precursor to a number of missions, primarily the Laser Interferometer Space Antenna (LISA). Team leadership responsibility for this concept was assigned to the Jet Propulsion Laboratory.

The ST5 technology announcement was released in late February and a total of 71 proposals were received by 22 March. Three technology suppliers (ILC Dover, L'Garde, and SRS Technologies) were selected for the Solar Sail team. Three technology suppliers (Busek Company, Stanford University, and the University of Colorado) were selected for the Disturbance Reduction Team. Eleven technology suppliers (Aero Astro, Bester Tracking Systems, the Charles Stark Draper Laboratory, two from the Jet Propulsion Laboratory, Lockheed Martin Astronautics, Marotta Scientific Controls, the University of Illinois, two from the NASA Goddard Space Flight Center, and Yardney Technical Products) were selected for the Small Satellite Constellation team.

In mid August 1999 NASA Headquarters selected the constellation of small satellites concept for continuation into detailed project formulation (step 16).

The ST5 project is discussed in greater detail in reference 7.

*Earth Orbiting 3 (EO3)*—The acquisition activities for EO3 differed in one major respect from those shown in Figures 5-7. These activities began with the NASA Headquarters release (in September 1998) of a NRA for measurement concepts best suited for orbits other than low-Earth orbit. Proposals were specifically encouraged for measurement concepts addressing the following science disciplines in the Office of Earth Science: Atmospheric Chemistry, Atmospheric Climate and Water Cycle, Ocean and Polar Science, Land Cover and Terrestrial Ecosystems, and Solid Earth and Natural Hazards. Twenty-four proposals were received in November 1998, and four concepts were selected in early March 1999. The concepts selected were a) active large aperture optical systems to provide high resolution thermal imaging from geosynchronous orbit (referred to as HORIZON), b) geostationary synthetic aperture microwave sounder (GEO/SAMS), c) geostationary imaging Fourier transform spectrometer (GIFTS), and d) geostationary tropospheric trace-gas imager (GEO-TRACE).

The HORIZON concept would demonstrate in space a large (2 to 3 meter) active-aperture telescope with a long-wave infrared focal plane array for making high resolution thermal images of regions on the Earth with high radiometric precision for use in environmental monitoring from geosynchronous orbit. This concept would offer more than an order-of-magnitude improvement in spatial

resolution performance of telescopes currently used for environmental monitoring from this orbit. This capability would enable the observation of environmental events in real time as they occur at the natural scale of the underlying phenomena: individual cells in hurricanes and tornadoes, volcanoes and fires, and the thermal patterns of oceans, rivers, valleys, snow fields and soil. This concept is based on a segmented mirror optical telescope assembly, an innovative approach for wavefront measurement for active control of the mirrors, and a large format uncooled long-wave IR detector array. Technologies to be validated are a deformable mirror, uncooled IR focal plane array, phase control (wavefront detection) using earth images, actuators for co-phasing primary mirror segments, and low-disturbance attitude control wheels.

The GEO/SAMS concept is a synthetic aperture microwave sounder operating in geostationary orbit that will provide measurement capabilities and accuracy similar to those current state-of-the-art atmospheric sounders operating in low-earth orbit. This concept achieves the required resolution without a large mechanically scanning antenna. This concept would have considerable impact on the operational user community, since it would enable the use of Geostationary Operational Environmental Satellite (GOES) data in numerical weather prediction at the same level of utility as data from the Polar-Orbiting Environmental Satellite (POES). It would be possible to generate long time series with complete coverage in time and space over a large region, which will greatly benefit researchers in mesoscale processes and climatology. This concept would also permit the probing of storms, including hurricanes, thus enabling severe-storm tracking in terms of temperature, water vapor, liquid water and precipitation distributions. The key technologies to be validated are small, light-weight multiple-receiver modules and a compact, low-power digital cross-correlator subsystem.

The GIFTS concept would use large-area format focal plane arrays to provide nearly continuous observation of large geographical areas with high horizontal resolution and a compact, light-weight Fourier transform spectrometer to produce simultaneous measurements of IR radiation spectra by each detector element with a spectral resolution sufficient for resolving the structure of the atmosphere with high vertical resolution. This concept offers a new capability to diagnose the profile of atmospheric wind velocity from the four-dimensional temperature and water vapor distribution. High resolution of water vapor can be used as a tracer for the specification of wind profiles. Dynamic observations of temperature, water vapor, and wind will enable a better understanding of climate physics, hydrology and the water cycle, the transport of chemical species, and weather processes. Key technologies to be validated are large-format IR focal plane arrays, lenslet arrays, a stable laser for precision scan mirror control, light-weight mirrors and telescopes and related optical pointing capability, data compression techniques, high-speed digital signal processor module specializing in fast Fourier

Transform processing, low-power A/D converters, and radiation mitigation techniques that enable the use of commercial-off-the-shelf electronics in geostationary orbits.

The GEO-TRACE concept consists of two coaligned sensors to form a nadir viewing sensor suite. The ozone sensor, an imaging spectrometer measuring solar backscatter in the near ultraviolet (UV) to visible spectral region, derives total ozone, stratospheric ozone, nitrogen dioxide, other trace species and aerosol density. The CO sensor measures carbon monoxide and reference gases ( $\text{CH}_4$  and  $\text{N}_2\text{O}$ ) in the 2.3 and 4.7  $\mu\text{m}$  spectral regions. This concept would enable tropospheric measurements of carbon monoxide, ozone, and nitrogen dioxide with a spatial resolution of 6-20 km at low and middle latitudes with a temporal resolution of 15 minutes. This particular suite of trace gas measurement would provide the data necessary to understand the physical and chemical processes responsible for the evolution and distribution of tropospheric ozone. Key technologies to be validated are large-area focal plane arrays (short wave and mid wave), large-area UV to NIR imaging array, high-resolution filter, 2-stage miniature cryocooler system, high-accuracy/low-noise gyro, advanced payload controller, and piezo-electric tuned etalons.

The EO3 technology announcement for concept study teams (step 9) was released in mid April 1999 and a total of 71 proposals were received by 5 May. Four technology suppliers (2 independent suppliers from Lockheed Martin Missiles and Space, Rockwell Science Center, and ERIM International) were selected for the HORIZON team. Four technology suppliers (GenCorp Aerojet, Lockheed/Sanders, TRW, and Lockheed Martin Space Electronics and Communications) were selected for the GEO/SAMS team. Eight technology suppliers (Lockheed Martin IR Imaging Systems, JPL and Indigo Systems Corporation, SSG, 2 independent suppliers from Honeywell Space Systems, Lockheed Martin Space Electronics and Communications, Raytheon Systems Company, and the University of New Mexico Microelectronics Research Center) were selected for the GIFTS team. Ten technology suppliers (3 from the Rockwell Science Center, MIT/Lincoln Laboratory, JPL, 2 from Lockheed Martin Missiles and Space, and Honeywell Space Systems) were selected for the GEO-TRACE team

In early December 1999 NASA Headquarters selected the GIFTS concept for continuation into detailed project formulation (step 16). Total project cost is capped at 105 M\$, and launch is scheduled for 2003.

## SUMMARY

Technology validation for future NASA science missions is a complex process that requires careful planning and execution. NASA created the New Millennium Program in 1995 to perform the technology validation needs for the NASA Office of Space Science and Office of Earth Science. The technology acquisition process used during the first two years of the NMP for the first three NMP missions (DS1,

DS2, and EO1) as well as some details of the technologies included in these projects were described. The refined NMP technology acquisition process was then described in detail with particular attention being paid to the "up front" planning activities (shown in Figure 7a) for mission concept development. The processes related to concept study team formation, technology acquisition, and concept selection for flight implementation were successfully implemented for the ST5 and EO3 projects.

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